Ground Testing of the Li-ion Batteries in Support of JPL's 2003 Mars Exploration Rover Mission

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In early 2004, JPL successfully landed two Rovers, named Spirit and Opportunity, on the surface of Mars after traveling > 300 million miles over a 6-7 month period. In order to operate for extended duration on the surface of Mars, both Rovers are equipped with rechargeable Lithium-ion batteries, which were designed to aid in the launch, correct anomalies during cruise, and support surface operations in conjunction with a triple-junction deployable solar arrays. The requirements of the Lithium-ion battery include the ability to provide power at least 90 sols on the surface of Mars, operate over a wide temperature range (–20°C to +40°C), withstand long storage periods (e.g., cruise period), operate in an inverted position, and support high currents (e.g., firing pyro events). In order to determine the viability of meeting these requirements, ground testing was performed on a Rover Battery Assembly Unit (RBAU), consisting of two 8-cell 8 Ah lithium-ion batteries connected in parallel. The RBAU upon which the performance testing was performed is nearly identical to the batteries incorporated into the two Rovers currently on Mars. The testing performed includes, (a) performing initial characterization tests (discharge capacity at different temperatures), (b) simulating the launch conditions, (c) simulating the cruise phase conditions (including trajectory corrections), (d) simulating the entry, decent, and landing pulse load profile (if required to support the pyros) (e) simulating the Mars surface operation mission simulation conditions, as well as, (f) assessing performance capacity loss and impedance characteristics as a function of temperature and life. As will be discussed, the lithium-ion batteries (fabricated by Lithion/Yardney, Inc.) were demonstrated to far exceed the requirements defined by the mission, and are projected to support an extended mission (> 2 years) with margin to spare.

I. Introduction

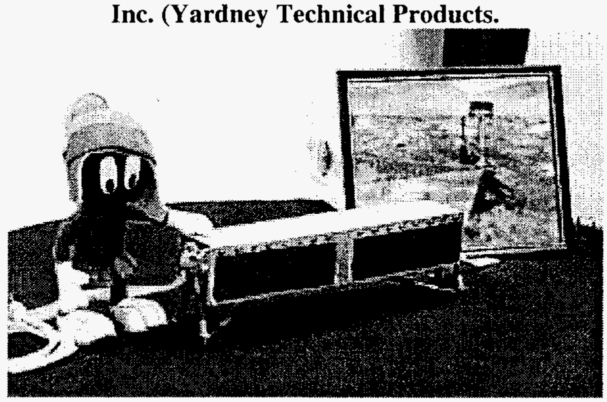
The Jet Propulsion Laboratory launched two spacecraft in 2003 (one on June 10 and the other on July 7) to explore the planet Mars in support of the Mars Exploration Rover (MER) mission.[1] Each spacecraft contained a robotic rover equipped with a number of instruments intended to analyze the Martian environment. After traveling over 300 million miles, the first spacecraft, carrying the first rover named "Spirit", landed successfully in Gusev crater on January 4, 2004, using an airbag landing system similar to that developed for the Mars Pathfinder mission. The second spacecraft, carrying the second rover named "Opportunity", also landed successfully 21 days later on the Meridiani Planum on Mars. The primary objective of the rover missions is to determine if water may have once been present on the planet and to assess the possibility that past environmental conditions could have sustained life. The two rovers were each designed to operate over a primary mission life of 90 sols (one sol, or martian solar day, has a mean period of ~ 24 hours and 39 minutes), with prelanding mission success being determined to be at least 600m being traversed by at least one of the rovers on the surface of Mars. To-date, both of the Mars roves have successfully completed the primary phase of their respective missions, leading NASA/JPL to extend the mission. As of June 27, 2005, the rover Spirit has completed 527 sols, whereas, Opportunity has successfully operated for 506 sols, thus, both exceeding the primary mission requirement by over 5 times to-date. In addition, Spirit has traveled over 4,580 meters since landing and Opportunity has logged over 5,340 meters (~ 3.3miles).

Key factors of the rover design which have led to the excellent life characteristics displayed on the surface of Mars include deployable solar arrays with triple-junction GaInP/GaAs/Ge cells which continue to generate power at high levels (in part, aided by periodic wind storms which remove dust from the surface of the solar arrays) and robust rechargeable lithium-ion batteries which continue to perform well with little loss in performance. In addition to providing power for mobility and communications, the power source enables the operation of a number of instruments, including a panoramic camera, two remote sensing instruments (a mini-thermal emission spectrometer and a mid-IR point spectrometer), and a number of *in-situ* pay-load elements (a Mossbauer spectrometer, an alpha-particle X-ray spectrometer, a microscopic imager, and a rock-abrasion tool). The role of the rechargeable lithium-ion batteries specifically is to augment the primary power source, the triple-junction solar arrays, and to provide power for nighttime operations. In addition to supporting the surface operations during the later phases of the missions, the lithium-ion batteries were also required to assist during the initial launch period and correct any possible anomalies occurring during the cruise period to Mars.[2] The purpose of this paper is to describe the attributes of the rechargeable lithium-ion batteries employed by the Mars rovers and to describe our efforts to assess their health and life characteristics by performing ground testing in support of the mission.

Rechargeable lithium-ion batteries were selected as the energy storage device for the rover design due to their high specific energy, good low temperature performance, low self-discharge, and high coulombic and energy efficiency. Due to the importance of limiting the mass and volume of the energy storage device, lithium-ion technology is especially attractive when compared with other battery chemistries, such as Ni-Cd, Ni-H_2, and Ag-Zn. The MER mission dictated that the rechargeable lithium-ion battery meet a number of requirements, including: 1) an operating voltage of 24-36V, 2) providing sufficient energy during launch (e.g., 220 Wh), 3) supporting any fault induced attitude excursion during the cruise period (e.g., 160 Wh), 4) providing sufficient energy for surface operations (at least 283 Wh/sol at 0°C), 5) providing sufficient cycle life (for at least 270 cycles at 50% DOD and/or 90 sols of operation), and 6) the ability to support multiple pulses of 30 A for 50mS, both at ambient and at low temperatures. In addition, the battery should display operational capability, both charge and discharge, over a wide temperature range (e.g., -20° to +30°C).

To meet these requirements, lithium-ion batteries were developed by Lithion, Inc. (Yardney Technical Products, Inc.), the Jet Propulsion Laboratory, USAF-WPAFB, and NASA-GRC under the 2003 MER project and a NASA-DoD consortium to develop aerospace quality lithium-ion cells/batteries.[3,4] The chemistry employed for the 2003 MER batteries was originally developed and demonstrated for the 2001 Mars Surveyor Program (MSP'01) lander battery, and consist of mesocarbon microbeads (MCMB) anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, and a low temperature electrolyte developed at JPL.[5,6,7,8] Although using similar chemistries, the MER mission necessitated the design of a smaller cell size (10 Ah, with an 8 Ah nameplate capacity) in contrast to the larger MSP'01 cell design (~ 33 Ah actual and 25 Ah nameplate capacity). Each rover was equipped with a Rover Battery Assembly Unit (RBAU), shown in Fig. 1, which consists of two 8-cell, 10 Ah batteries connected in parallel. The RBAU was designed such that each battery would be cycled to typically 40-50% depth-of-discharge each sol, or in the event one battery failed to operate the other battery could support the primary mission needs. During the course of the project, Lithion, Inc. fabricated and delivered seven RBAUs to JPL (two flight, one space, one ATLO, and three engineering units). The results described below involve the electrical performance testing that was performed of one of these RBAUs, which was dedicated to mission simulation ground testing.

Figure 1. Lithium-ion RBAU fabricated by Lithion, Inc. (Yardney Technical Products.



II. Performance Testing of Rover Battery Assembly Units

Upon receipt of the RBAUs from Lithion, Inc., standard acceptance testing was performed on all units to verify the performance. This consisted of: (a) measuring the isolation resistance, (b) performing electrical continuity measurements, (c) performing capacity determination tests at 20 and –20°C, (d) performing capacity stand test (72 hours OCV), (e) verifying the integrity of the thermal hardware, and (g) general visual examination of workmanship. In addition to performing acceptance testing, a number of mission specific electrical test were performed on the ATLO battery after completing its primary function, serving as a characterization and mission simulation battery. This testing consisted of, (a) determining the capacity and cycling characteristics at different temperatures (-30 to 20°C), throughout the life of the battery (b) performing current interrupt impedance measurements, (c) performing launch and cruise operation simulation tests, (d) performing clock operation simulation testing (e) performing cruise period storage simulation testing (10 months on the bus at ~ 70% SOC), and (f) performing surface operation mission simulation testing. The intent of the testing program was to closely mirror the conditions anticipated for the two rovers and generate comparable real time data, while periodically performing health diagnostic tests to allow for estimation of capacity and performance decline. Due to the complex nature of the load profile, the fluctuating thermal conditions experienced, and the shallow depth of discharge (40-50%) experienced by the two rovers on Mars, it is difficult to assess battery degradation characterization accurately. Thus, the mission simulation battery has greatly aided in lifetime predications of battery health that have been helpful to mission planners.

A. Acceptance Testing

As mentioned previously, upon receiving the RBAUs from Lithion, Inc. a number of acceptance tests were performed to assess the health of the batteries. As shown in Fig. 2 and 3, the capacity determination testing initially consisted of performing 2 ½ cycles at 20°C using a 10 hour constant current charge rate (C/10) to 32.40 V and a constant potential charge until the current decays to C/5, followed by constant current discharge to 24.00 V. As illustrated in the figures below, over 10 Ah was delivered at 20°C under the conditions described.. Similar electrical characterization tests were performed at -20°C and observed to deliver 7.806 Ah with a room temperature charge and 7.288 Ah with a charge at -20°C. Given the low charge voltage (corresponding to 4.05 V per cell), more capacity can be delivered using higher charge voltages. During the course of all electrical characterization tests, all cells voltages are actively monitored and recorded and if the values fall beyond prescribed safety limits the test is terminated. Unlike the operation of the batteries on Mars, active cell charge control is not implemented during the ground testing of the batteries. Instead, manual cell balancing is performed on an as-needed basis, and is typically performed prior to major characterization events (i.e., upon receipt, before and after cruise characterization, and after completing 90 sol increments of surface operation simulation) or if the cell dispersion exceeds ~ 0.150 V. This manual cell balancing consists of resistively discharging the cells to a set voltage, such that the cells adopt similar states-of-charge. Our experience has been that the most efficient method of cell balancing involves resistively discharging the cells to a mid SOC (i.e., corresponding to ~ 3.7 V at the cell level), rather than balancing a very low or high SOC.

Figure 2. Capacity determination acceptance testing of RBAU 4A at 20°C.

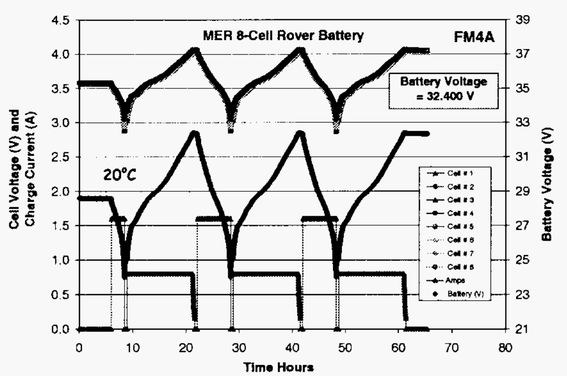
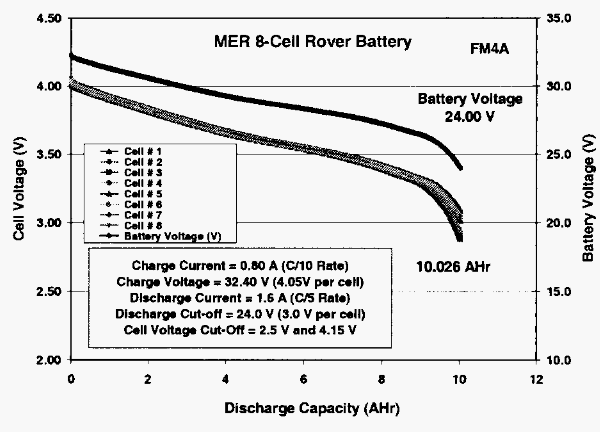


Figure 3. Initial discharge capacity determination at 20°C (C/5 discharge, 32.40 V charge)



In addition to assessing the capacity at different temperature, current interrupt-impedance measurements were performed on the batteries as means of determining the impedance of the batteries (and cells) as a function of state-of-charge and how this changes as a function of life. As shown in Fig. 4, the impedance measurements consisted of subjecting the batteries to 5 amp discharge pulses of 60 second duration at four different states-of-charge (100, 75, 50, and 25% SOC). Given the dynamic nature of the battery impedance, it is necessary to consistently use the same pulse duration and amplitude; otherwise the measurements will reflect different contributions of ohmic, charge transfer, and diffusional impedances. In addition, to performing these tests at different temperatures, they were repeated throughout the batteries' lifetimes to indicated the extent to which the impedance is increasing.

Figure 4. Current-interrupt impedance measurements of RBAU 4A at 0°C.

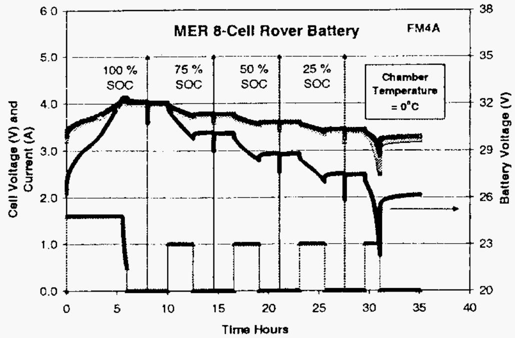
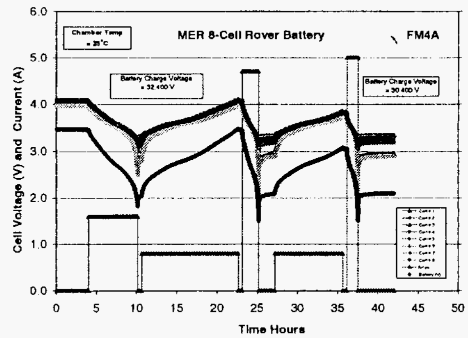


Figure 5. Launch and cruise anomaly correction profile at 23°C.



B. Simulation of Launch, Cruise, and EDL

Since the main objective of performing mission simulation ground testing is to provide meaningful input regarding battery health and operating characteristics throughout the mission, there was a concerted attempt to device a test plan which closely mirrors the conditions anticipated by the two flight batteries of Spirit and; Opportunity. One of the initial tests performed involved simulating the conditions projected for the launch period, which was supported by the Li-ion batteries, and the loads expected to be endured by the battery during cruise for the purpose of correcting trajectory anomalies, if needed. To simulate these conditions, the batteries were discharged at 4.70 amps (~ C/2 rate) to 20 V at 25°C after being charged to ~ 95% SOC, or 32.40 V, (launch conditions) and discharged at 5.00 amps (C/2 rate) to 20 V at 25°C after being charged to ~ 70% SOC, or 30.4 V (cruise anomaly corrections), as shown in Fig. 5. As expected, the batteries were demonstrated to provide the requisite energy to support these operations.

Figure 6. Cruise period simulation at 10°C consisting of storage on the bus

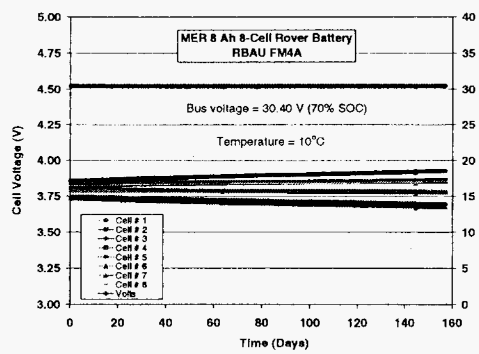
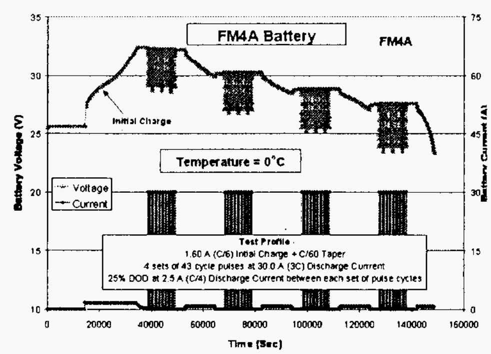


Figure 7. EDL Profile at 0°C.



Another critical test involved simulating the cruise storage period, in which the battery is connected to the bus at a preset voltage for long duration. Due to concerns of storing the batteries in a high SOC, lower states of charge a desirable to minimize the extent of permanent capacity loss and impedance growth. However, in order to provide sufficient energy to support the anomaly corrections, if needed, the project desired higher SOCs. Thus, the battery was stored at ~ 70% SOC, corresponding to 30.40 V, which had previously been demonstrated to result in minimal performance losses under theMSP'01 program using similar chemistry. As shown in Fig. 6, significant cell dispersion was observed to occur during this long storage period (~ 7 months), which emphasizes the need for charge control with this type of chemistry for extended missions. From our experience of testing multi-cell Li-ion batteries, we have observed greater cell dispersion to occur under storage periods such as this, in contrast to continuous cycling. During the actual missions, the batteries on Spirit and Opportunity were balanced ~ 8 times prior to the arrival on the surface of Mars, as explained in detail in our companion paper.[9] As described later, minimal permanent capacity loss was observed as a result of being subjected to the storage period.

After completing the storage period, the batteries were subjected to an Entry, Descent, and Landing (EDL) load profile. Although primary Li-SO_2 batteries were designed to support these operations, the Li-ion batteries served as a backup in the event of any problem with the primary battery. This test consisted of applying 30 amp pulses (3C rate) to the battery at five different states-of-charge (SOC) at 0°C, as illustrated in Fig. 7. In total, 4 groups of 43 pulses were applied to battery, each pulse being 50 mSec in duration and each pulse being separated from one another by 100 mSec. As shown, the battery successfully supports the operation, which powers the pyro events during the EDL sequence, even at low SOC. Although the lithium-ion batteries were demonstrated to have the capability to perform the EDL profile, the primary Li-SO_2 batteries worked perfectly and supported the mission as designed.

C. Surface Operation Mission Simulation Profile

After completing the cruise period and EDL simulation testing, the batteries were subjected to a test plan that attempted to closely mirror the surface operation conditions of the batteries once they reached the surface of Mars. Generally, this involved performing ~ 50% DOD cycling over a wide temperature range (Δ ~ 20 °C), with one cycle being performed each Martian sol (= 24.35 earth hours). Prior to performing this test on the mission simulation RBAU, numerous permutations of the expected surface operation profiles were performed at the cell level to understand the margins of performance. As shown in Fig. 8, the initial surface operation profile was implemented over a relatively cold temperature range (-20 to 0°C). Upon receiving actual data from the Mars rovers, it was determined that the actual temperatures were much warmer. Thus, the subsequent surface profiles were modified to warmer temperatures to more closely mirror the conditions experienced by the rovers (implemented after completing 90 sols). In addition, the temperature profiles were adjusted to reflect the changing seasons on Mars. Furthermore, the actual load profile was modified during the course of testing, based on actual telemetry data to reflect the average condition over a range of sols. For example, the load profile implemented on the mission simulation battery after completing 180 sols is illustrated in Fig. 8, which was based on mission telemetry data and involves a temperature profile ranging from – 2.5°C to 16°C. To date, over 380 sols of surface operation have been simulated during the ground testing of the RBAU. Although the testing started well before the launch of the mission, the implementation of periodic health tests and sporadic test suspensions due to facilities shut downs have caused the batteries to lag behind in the number of cycles accumulated.

Figure 8. Initial surface operation load and temperature profile.

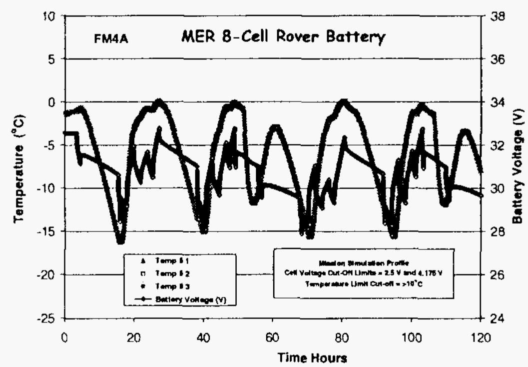
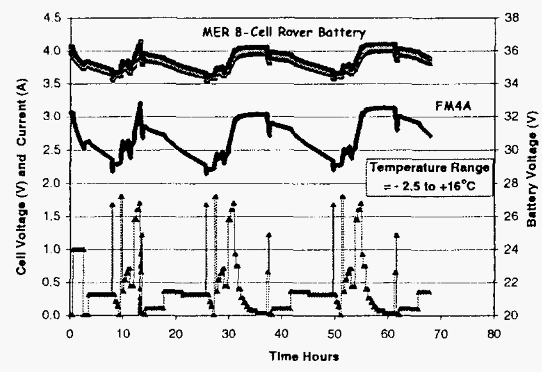


Figure 9. Modified mission simulation surface operation profile implemented after 180 sols.



C. Capacity and Impedance Determination During Surface Operation Testing

As mentioned previously, both 100% DOD capacity checks and current-interrupt impedance measurements were performed at different temperatures every 90 sols to determine the health characteristics of the batteries and to aid in estimates of the permanent capacity loss and impedance growth experienced by the batteries on Spirit and Opportunity. Prior to performing the capacity and impedance determination, the cells within the batteries were balanced so as to obtain full capacity and optimal performance, as well as to closely mirror the conditions experienced on the two rovers. In summary, excellent performance has been obtained thus far, which is encouraging to the project and factors into the decisions to extend the mission further. As shown in Table 1, one of the batteries still exhibits 93.3 % of the initial capacity after completing the cruise period and 360 sols of surface operation simulation. The other battery shows very complementary data with 92.8 % of the original capacity being displayed, emphasizing the good reproducibility of the data between the two batteries. As shown in Fig. 9, the voltage profile during the 100% DOD capacity checks performed every 90 sols displays little change. As expected, the capacity losses are more significant at the lower temperatures, due to the increased polarization effects compounded by increased impedance growth as a function of

Table 1. Entry-Descent-and-Landing testing of a MER design 10 Ahr lithium ion cell.

FM4B	Performance Prior to Cruise		Performance After Cruise and Completing 90 Sols				Performance After Cruise and Completing 180 Sols				Performance After Cruise and Completing 270 Sols				[redacted]			
Temperature (°C)	Discharge Capacity (Ah)	Discharge Energy (Wh)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)
20°C	10.048	289.6	9.742	96.96	280.1	96.69	9.611	95.65	275.8	95.24	9.543	94.98	273.4	94.38	9.448	94.03	270.3	93.32
0°C*			8.991		254.8		8.897		251.6		8.799		248.3		8.632		242.8	
- 20°C*	7.864	215.9	7.295	92.77	198.6	91.98	7.063	89.81	191.7	88.76	6.929	88.11	187.9	87.04	6.710	7.30	181.1	83.89
- 30°C*							5.759		150.2		5.420		140.4		5.364		139.3	

life. However, the batteries both display operational capability at temperatures as low as -30oC late in life, with over 56 % of the room temperature capacity being delivered with a room temperature charge. In addition to assessing the low temperature capabilities with ambient temperature charging, cycling was performed with the charging occurring at the respective temperatures. Expectedly, the capacity delivered is lower under these conditions; however, good performance was obtained using low temperature charge. For example, only 6% less capacity was delivered at -20°C following charge at that temperature, while 12% less capacity was delivered at -30°C. Fortunately, since the charge period of the rovers is during daylight hours, the latter stages of the charging are occurring while the temperatures are warmer.

In addition to assessing the capacity losses as a function of life, the impedance of the batteries and the cells has been determined by indirectly by performing current-interrupt testing. As mentioned previously, it is important to consistently impose identical pulsing conditions to make meaningful conclusions. Due to the fact that it is difficult to determine the precise SOC and state of health of the batteries on Mars (since the coulometer is no longer providing traceable input), an enhanced understanding of the impact that capacity loss and impedance growth have upon the polarization behavior is of great benefit. For this reason, we have been systematically performing impedance measurements at various states-of-charge and temperatures throughout the life of the batteries. As shown in Table 2, the impedance of the battery steady increases as a function of cycle life, being more dramatic at lower temperatures. As illustrated, after completing 360 sols of the surface operation profile and the ~ 7 month cruise period one of the batteries displayed approximately a 55% increase in the impedance measured (the second battery displaying ~ 57% increase). Although an incomplete data set was performed immediately after the cruise period, it appears as though the greatest increase in impedance was sustained in the first 90 sols of operation.

Figure 9. Discharge capacity (100 % DOD) at 20°C as a function of surface operation life.

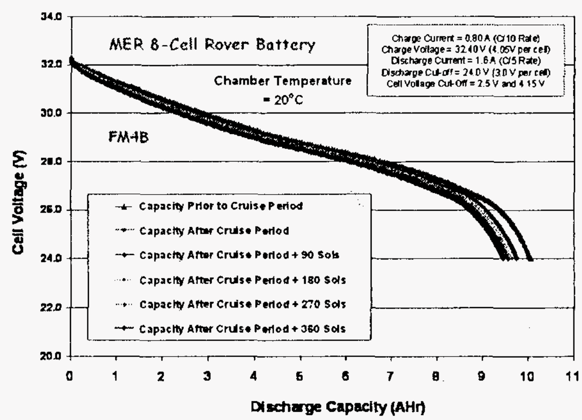


Figure 10. Impedance measurements as a function of cycle life.

FM4B	Performance Prior to Cruise	Performance After Cruise		Performance After Cruise and Completing 90 Sols		Performance After Cruise and Completing 180 Sols		Performance After Cruise and Completing 270 Sols		[redacted]	
Temp (°C)	Battery Impedance (mOhms)	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance
20°C	118.16			155.10	31.26	164.6	39.30	172.8	46.24	183.0	54.87
0°C*	241.70	283.04	17.10	354.84	46.81	379.7	57.08	396.6	64.09	421.6	74.44
- 20°C	589.91			871.26	47.69	922.8	56.42	925.9	56.96	938.2	59.04
- 30°C						1372.4		1408.2		1406.0	

As mentioned previously, a major objective of performing the 100% DOD and impedance characterization tests was as a means of assessing the battery health to aid in life predictions in support of the mission. Given the difficulty of assessing the life characteristics from telemetry data, the data generated from the ground testing of an identical battery subjected to comparable conditions proved to be crucial in assessing the viability of the technology to support a prolonged mission (i.e., at least three years in duration). As shown in Fig. 10, to-date only 6-7 % capacity loss has been observed on both batteries as a result of being subjected to 360 sols, the 7 month cruise period, and intermittent characterization (total test time > 2.6 years). Also significant is the fact that only ~ 1% capacity loss has been sustained as a result of the last 90 sols of testing, even though the temperature regime has been warmer during this period. This data suggests that the fade rate and degradation processes are more dramatic early in life and that the losses are leveling off. A simple extrapolation of the life data suggests that over 80% of the initial capacity delivered at 20°C will remain after completing 1400 sols (over 3.5 years), as illustrated in Fig. 11. Of course, the losses in low temperature capability are certain to be more dramatic, however, with careful management the batteries should be capable of supporting the mission well into the future.

Figure 10. Percent of initial capcity observed with both FM$A and FM4B of the mission simulation battery.

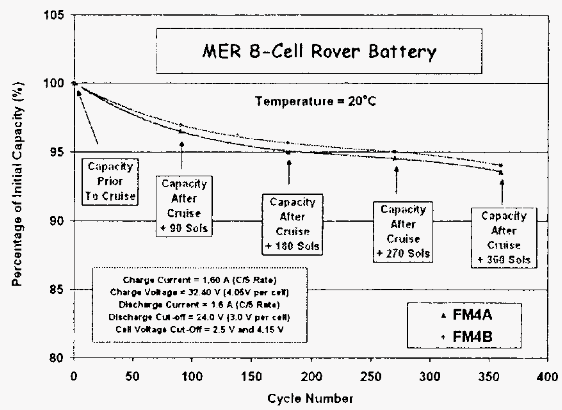
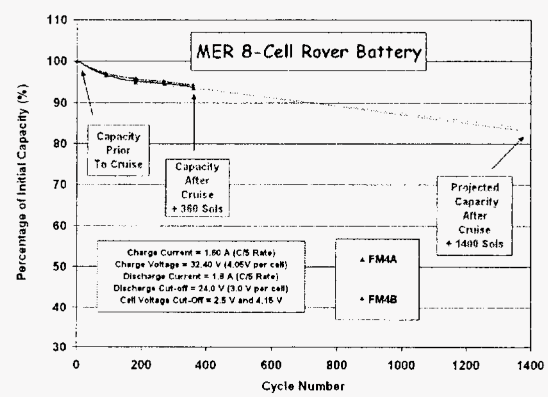


Figure 11. Individual cell impedance values obtained from a MER Rover 8-cell lithium-ion battery as a function of life



III. Conclusion

To support the operation of Spirit and Opportunity on Mars, on-going mission simulation ground testing has been performed at JPL. This testing has included, (a) performing initial characterization tests (discharge capacity at different temperatures), (b) simulating the launch conditions, (c) simulating the cruise phase conditions (including trajectory corrections), (d) simulating the entry, decent, and landing pulse load profile (if required to support the pyros) (e) simulating the Mars surface operation mission simulation conditions, as well as, (f) assessing performance capacity loss and impedance characteristics as a function of temperature and life. These tests have demonstrated that the technology meets or exceeds all mission requirements, most notably displaying excellent cycle life characteristics, far exceeding the requirement of 90 sols of operation. To-date, the mission simulation batteries have only displayed 6-7 % permanent capacity loss after being subjected to 7 months of storage, 360 surface operation sols, and intermittent characterization testing (over 2.6 years of total test time). Based on data generated from the ground testing of this engineering battery, current projections indicate that the batteries on Spirit and Opportunity can support an extended mission well into the future (> 1000 sols), while still exhibiting over 80% of the initial capacity at ambient temperatures. Due to seasonal changes in temperature and solar intensity, the coming winter months are more demanding on battery and solar array performance, however, with proper management the rovers have the potential to work well into the future.

Acknowledgments

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FINAL

Ground Testing of the Li-ion Batteries in Support of JPL's 2003 Mars Exploration Rover Mission

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In early 2004, JPL successfully landed two Rovers, named Spirit and Opportunity, on the surface of Mars after traveling > 300 million miles over a 6-7 month period. In order to operate for an extended duration (9 months) on the surface of Mars, both Rovers are equipped with rechargeable Lithium-ion batteries, which were designed to aid in the launch and the EDL pyros, allow for anomalies during cruise, and support surface operations in conjunction with a triple-junction deployable solar arrays. The requirements of the Lithium-ion battery include the ability to provide power at least 90 sols on the surface of Mars, operate over a wide temperature range (–20°C to +30°C), withstand long storage periods (e.g., cruise period), operate in an inverted orientation, and support high current pulses (e.g., firing pyro events). In order to determine the viability of meeting these requirements, ground testing was performed on a Rover Battery Assembly Unit (RBAU), consisting of two 8-cell 10 Ah lithium-ion batteries connected in parallel. The RBAU upon which the performance testing was performed is nearly identical to the batteries incorporated into the two Rovers currently on Mars. The testing includes, (a) performing initial characterization tests (discharge capacity at different temperatures), (b) simulating the launch conditions, (c) simulating the cruise phase conditions (including trajectory correction manuevers), (d) simulating the entry, decent, and landing (EDL) pulse load profile (required to support the pyros) (e) simulating the Mars surface operation mission simulation conditions, as well as, (f) assessing capacity loss and impedance characteristics as a function of temperature and life. As will be discussed, the lithium-ion batteries (fabricated by Lithion/Yardney, Inc.) were demonstrated to far exceed the requirements defined by the mission, and are projected to support an extended mission (> 2 years) with margin to spare.

I. Introduction

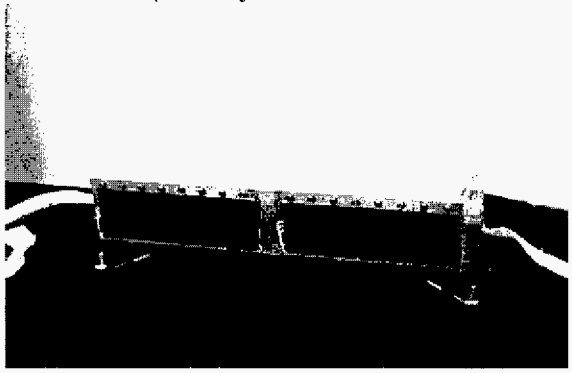
The Jet Propulsion Laboratory launched two spacecraft in 2003 (one on June 10 and the other on July 7) to explore the planet Mars in support of the Mars Exploration Rover (MER) mission.[1] Each spacecraft contained a robotic rover equipped with a number of instruments intended to analyze the Martian environment. After traveling over 300 million miles, the first spacecraft, carrying the first rover named "Spirit", landed successfully in Gusev crater on January 4, 2004, using an airbag landing system similar to that developed for the Mars Pathfinder mission. The second spacecraft, carrying the second rover named "Opportunity", also landed successfully 21 days later on the Meridiani Planum on Mars. The primary objective of the rover missions is to determine if water may have once been present on the planet and to assess the possibility that past environmental conditions could have sustained life. The two rovers were each designed to operate over a primary mission life of 90 sols (one sol, or martian solar day, has a mean period of ~ 24 hours and 39 minutes), with mission success being determined, in part, to be at least 600m being traversed by at least one of the rovers on the surface of Mars. To-date, both of the Mars rovers have successfully completed the primary phase of their respective missions, leading NASA/JPL to extend the mission twice. As of June 27, 2005, the rover Spirit has completed 527 sols, whereas, Opportunity has successfully operated for 506 sols, thus, both exceeding the primary mission requirement by over 5 times to-date. In addition, Spirit has traveled over 4,580 meters since landing and Opportunity has logged over 5,340 meters (~ 3.3miles).

Key factors of the rover design which have led to the excellent life characteristics displayed on the surface of Mars include deployable solar arrays with triple-junction GaInP/GaAs/Ge cells which continue to generate power at high levels (in part, aided by periodic wind storms which remove dust from the surface of the solar arrays) and robust rechargeable lithium-ion batteries which continue to perform well with little loss in performance. In addition to providing power for mobility and communications, the power source enables the operation of a number of instruments, including two remote sensing instruments (a mini-thermal emission spectrometer and a panoramic camera), and a number of *in-situ* pay-load elements (a Mossbauer spectrometer, an alpha-particle X-ray spectrometer, a microscopic imager, and a rock-abrasion tool). The role of the rechargeable lithium-ion batteries specifically is to augment the primary power source, the triple-junction solar arrays, and to provide power for nighttime operations. In addition to supporting the surface operations during the later phases of the missions, the lithium-ion batteries were also required to assist during the initial launch period, allow time to correct any possible anomalies occurring during the cruise period to Mars, and support EDL pyros. [2] The purpose of this paper is to describe the attributes of the rechargeable lithium-ion batteries employed by the Mars rovers and to describe our efforts to assess their health and life characteristics by performing ground testing in support of the mission.

Rechargeable lithium-ion batteries were selected as the energy storage device for the rover design due to their high specific energy, good low temperature performance, low self-discharge, and high coulombic and energy efficiency. Due to the importance of limiting the mass and volume of the energy storage device, lithium-ion technology is especially attractive when compared with other battery chemistries, such as Ni-Cd, $Ni\text{-}H_2$, and Ag-Zn. The MER mission dictated that the rechargeable lithium-ion battery meet a number of requirements, including: 1) an operating voltage of 24-36V, 2) providing sufficient energy during launch (e.g., 220 Wh), 3) supporting any fault induced attitude excursion during the cruise period (e.g., 160 Wh), 4) providing sufficient energy for surface operations (at least 283 Wh/sol at 0°C), 5) providing sufficient cycle life (for at least 270 cycles at 50% DOD and/or 90 sols of operation), and 6) the ability to support multiple pulses of 30 A for 50mS, both at ambient and at low temperatures. In addition, the battery should display operational capability, both charge and discharge, over a wide temperature range (e.g., -20° to +30°C).

To meet these requirements, lithium-ion batteries were developed by Lithion, Inc. (Yardney Technical Products, Inc.), the Jet Propulsion Laboratory, USAF-WPAFB, and NASA-GRC under the 2003 MER project and a NASA-DoD consortium to develop aerospace quality lithium-ion cells/batteries.[3,4] The chemistry employed for the 2003 MER batteries was originally developed and demonstrated for the 2001 Mars Surveyor Program (MSP'01) lander battery, and consist of mesocarbon microbeads (MCMB) anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, and a low temperature electrolyte developed at JPL. [5, 6, 7, 8] Although using similar chemistries, the MER mission necessitated the design of a smaller cell size (10 Ah, with an 8 Ah nameplate capacity) in contrast to the larger MSP'01 cell design (~ 33 Ah actual and 25 Ah nameplate capacity). Each rover was equipped with a Rover Battery Assembly Unit (RBAU), shown in Fig. 1, which consists of two 8-cell, 10 Ah batteries connected in parallel. The RBAU was designed such that each battery would be cycled to typically 40-50% depth-of-discharge each sol, or in the event one battery failed to operate the other battery could support the primary mission needs. During the course of the project, Lithion, Inc. fabricated and delivered seven RBAUs to JPL (two flight, one flight spare, one ATLO, and three engineering units). The results described below involve the electrical performance testing that was performed on the ATLO RBAU, which was dedicated to mission simulation ground testing.

Figure 1. Lithium-ion RBAU fabricated by Lithion, Inc. (Yardney Technical Products.



II. Performance Testing of Rover Battery Assembly Units

Upon receipt of the RBAUs from Lithion, Inc., standard acceptance testing was performed on all units to verify the performance. This consisted of: (a) measuring the isolation resistance, (b) performing electrical continuity measurements, (c) performing capacity determination tests at 20 and –20°C, (d) performing capacity stand test (72 hours OCV), (e) verifying the integrity of the thermal hardware, and (f) general visual examination of workmanship. In addition to performing acceptance testing, a number of mission specific electrical tests were performed on the ATLO battery after completing its primary function, doubling as a characterization and mission simulation battery. This testing consisted of, (a) determining the capacity at different temperatures (-30 to 20°C), throughout the cycle life testing of the battery (b) performing current interrupt impedance measurements, (c) performing launch and cruise operation simulation tests, (d) performing clock operation simulation testing, (e) performing cruise period storage simulation testing (10 months on the bus at ~ 70% SOC), and (f) performing surface operation mission simulation testing. The intent of the testing program was to closely mirror the conditions anticipated for the two rovers and generate comparable real time data, while periodically performing health diagnostic tests to allow for determination of capacity and performance decline. Due to the complex nature of the load profile, the fluctuating thermal conditions experienced, and the shallow depth of discharge (40-50%) experienced by the two rovers on Mars, it is difficult to assess battery degradation characterization accurately on the spacecraft. Thus, the mission simulation battery has greatly aided in lifetime predications of battery health that have been helpful to mission operations.

A. Acceptance Testing

As mentioned previously, upon receiving the RBAUs from Lithion, Inc. a number of acceptance tests were performed to assess the health of the batteries. As shown in Fig. 2 and 3, the capacity determination testing of the ATLO RBAU (4A) initially consisted of performing 2 ½ cycles at 20°C using a 10 hour constant current charge rate (C/10) to 32.40 V and a constant potential charge until the current decays to C/50, followed by constant current discharge to 24.00 V. As illustrated in the figures below, over 10 Ah was delivered at 20°C under the conditions described. Similar electrical characterization tests were performed at -20°C and observed to deliver 7.806 Ah with a room temperature charge and 7.288 Ah with a charge at -20°C. Given the low charge voltage (corresponding to 4.05 V per cell), more capacity can be delivered using higher charge voltages. Indeed, higher charge voltages (i.e., 32.80V were routinely used throughout the mission, however, 32.40 V was chosen for all characterization tests to avoid high individual cell voltages in the event of wide cell voltage dispersion and to remain consistent throughout all testing. During the course of all electrical characterization tests, all cells voltages are actively monitored and recorded and if the values fall beyond prescribed safety limits the test is terminated. Unlike the operation of the batteries on Mars, active cell charge control is not implemented during the ground testing of the batteries. Instead, manual cell balancing is performed on an as-needed basis, and is typically performed prior to major characterization events (i.e., upon receipt, before and after cruise characterization, and after completing 90 sol increments of surface operation simulation) or if the cell dispersion exceeds ~ 0.150 V. This manual cell balancing consists of resistively discharging the cells to a set voltage, such that the cells adopt similar states-of-charge. Our experience has been that the most efficient method of cell balancing involves resistively discharging the cells to a mid SOC (i.e., corresponding to ~ 3.7 V at the cell level), rather than balancing a very low or high SOC.

Figure 2. Capacity determination acceptance testing of RBAU 4A at 20°C.

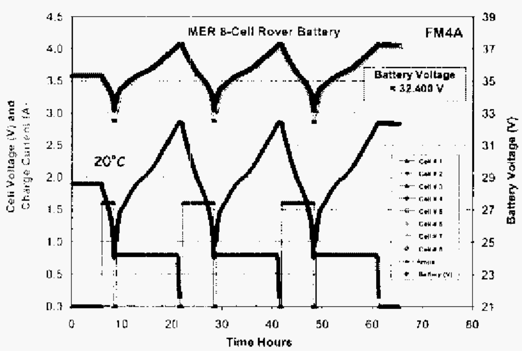
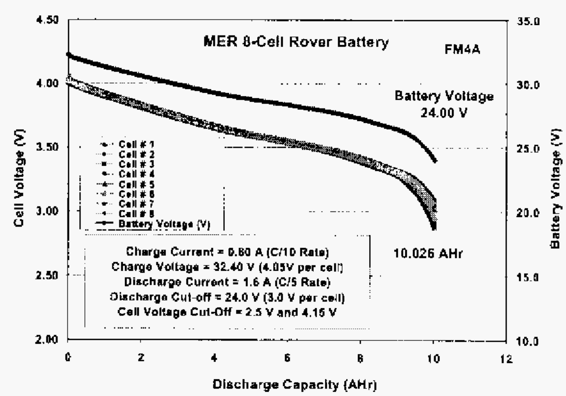


Figure 3. Initial discharge capacity determination at 20°C (C/5 discharge, 32.40 V charge)



In addition to assessing the capacity at different temperatures, current interrupt-impedance measurements were performed on the batteries as a means of determining the impedance of the batteries (and cells) as a function of state-of-charge, and how this changes as a function of life. As shown in Fig. 4, the impedance measurements consisted of subjecting the batteries to 5 amp discharge pulses of 60 second duration at four different states-of-charge (100, 75, 50, and 25% SOC). Given the dynamic nature of the battery impedance, it is necessary to consistently use the same pulse duration and amplitude; otherwise the measurements will reflect different contributions of ohmic, charge transfer, and diffusional impedances. In addition to performing these tests at different temperatures, they were repeated throughout the batteries' lifetimes to indicate the extent to which the impedance is increasing.

Figure 4. Current-interrupt impedance measurements of RBAU 4A at 0°C.

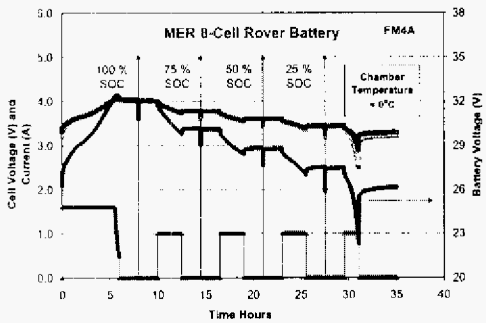
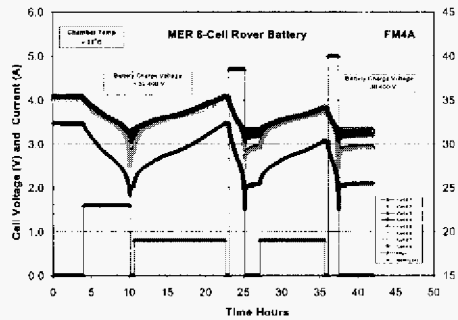


Figure 5. Launch and cruise trajectory correction maneuver profile at 23°C.



B. Simulation of Launch, Cruise, and EDL

Since the main objective of performing mission simulation ground testing is to provide meaningful input regarding battery health and operating characteristics throughout the mission, there was a concerted attempt to device a test plan which closely mirrors the conditions anticipated by the two flight batteries of Spirit and Opportunity. One of the initial tests performed involved simulating the conditions projected for the launch period, which was supported by the Li-ion batteries, and the loads expected to be endured by the battery during cruise for the purpose of correcting trajectory anomalies, if needed. To simulate these conditions, the batteries were discharged at 4.70 amps (~ C/2 rate) to 20 V at 25°C after being charged to ~ 95% SOC, or 32.40 V, (launch conditions) and discharged at 5.00 amps (C/2 rate) to 20 V at 25°C after being charged to ~ 70% SOC, or 30.4 V (cruise anomaly corrections), as shown in Fig. 5. As expected, the batteries were demonstrated to provide the requisite energy to support these operations.

Figure 6. Cruise period simulation at 10°C consisting of storage on the bus.

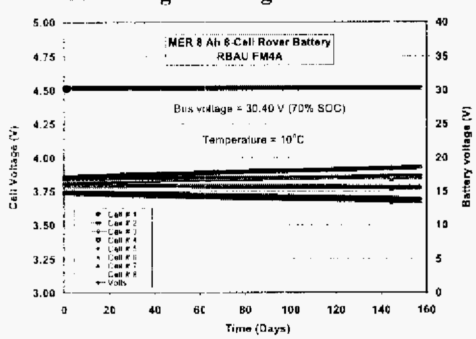
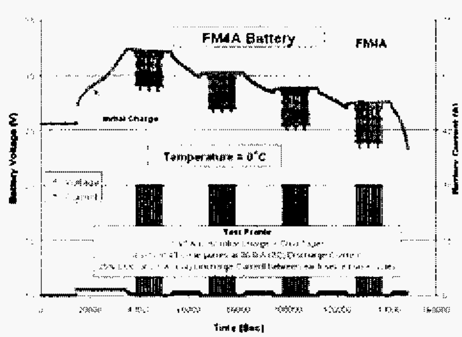


Figure 7. EDL Profile at 0°C.



Another critical test involved simulating the cruise storage period, in which the battery is connected to the bus at a preset voltage for long duration. Due to concerns of storing the batteries in a high SOC, lower states of charge are desirable to minimize the extent of permanent capacity loss and impedance growth. However, in order to provide sufficient energy to support the anomaly corrections, if needed, the project desired higher SOCs. Thus, the battery was stored at ~ 70% SOC, corresponding to 30.40 V, which had previously been demonstrated to result in minimal performance losses under the MSP'01 program using similar chemistry. As shown in Fig. 6, significant cell dispersion was observed to occur during this long storage period (~ 7 months), which emphasizes the need for charge control with this type of chemistry for extended missions. From our experience of testing multi-cell Li-ion batteries, we have observed greater cell dispersion to occur under storage periods such as this, in contrast to continuous cycling. During the actual missions, the batteries on Spirit and Opportunity were balanced ~ 8 times prior to the arrival on the surface of Mars, as explained in detail in our companion paper.[9] As described later, minimal permanent capacity loss was observed as a result of being subjected to the storage period.

After completing the storage period, the batteries were subjected to an Entry, Descent, and Landing (EDL) load profile. In addition to the $Li\text{-}SO_2$ batteries and thermal batteries which provided power during the EDL process, the Li-ion batteries served to support a number of pyro events prior to landing. The verification test consisted of applying 30 amp pulses (3C rate) to the battery at four different states-of-charge (SOC) at 0°C, as illustrated in Fig. 7. In total, 4 groups of 43 pulses were applied to battery, each pulse being 50 mSec in duration and each pulse being separated from one another by 100 mSec. As shown, the battery successfully supports the operation, which powers the pyro events during the EDL sequence, even at low SOC. Although the lithium-ion batteries were demonstrated to have the capability to perform the EDL profile, the primary $Li\text{-}SO_2$ batteries worked perfectly and supported the mission as designed.

C. Surface Operation Mission Simulation Profile

After completing the cruise period and EDL simulation testing, the batteries were subjected to a test plan that attempted to closely mirror the surface operation conditions of the batteries once they reached the surface of Mars. Generally, this involved performing ~ 50% DOD cycling over a wide temperature range (Δ ~ 20 °C), with one cycle being performed each Martian sol (= 24.35 earth hours). Prior to performing this test on the mission simulation RBAU, numerous permutations of the expected surface operation profiles were performed at the cell level to understand the margins of performance. As shown in Fig. 8, the initial surface operation profile was implemented on the RBAU over a relatively cold temperature range (-20 to 0°C). Upon receiving actual data from the Mars rovers, it was determined that the actual temperatures were much warmer. Thus, the subsequent surface profiles were modified to warmer temperatures to more closely mirror the conditions experienced by the rovers (implemented after completing 90 sols). In addition, the temperature profiles were adjusted to reflect the changing seasons on Mars. Furthermore, the actual load profile was modified during the course of testing, based on actual telemetry data to reflect the average condition over a range of sols. For example, the load profile implemented on the mission simulation battery after completing 180 sols is illustrated in Fig. 9, which was based on mission telemetry data and involves a temperature profile ranging from – 2.5°C to 16°C. To date, over 380 sols of surface operation have been simulated during the ground testing of the RBAU. Although the testing started well before the launch of the mission, the implementation of periodic health tests and sporadic test suspensions due to facilities shut downs have caused the batteries to lag behind in the number of cycles accumulated (or sols simulated).

Figure 8. Initial surface operation load and temperature profile.

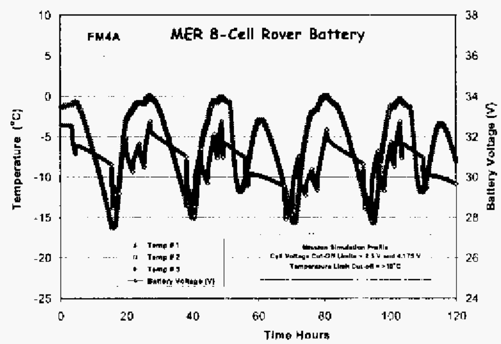
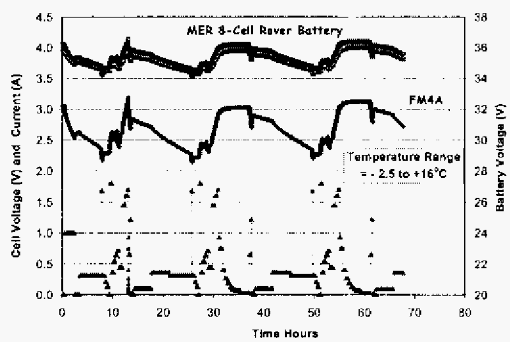


Figure 9. Modified mission simulation surface operation profile implemented after 180 sols.



C. Capacity and Impedance Determination During Surface Operation Testing

As mentioned previously, both 100% DOD capacity checks and current-interrupt impedance measurements were performed at different temperatures every 90 sols to determine the health characteristics of the batteries and to aid in estimates of the permanent capacity loss and impedance growth experienced by the batteries on Spirit and

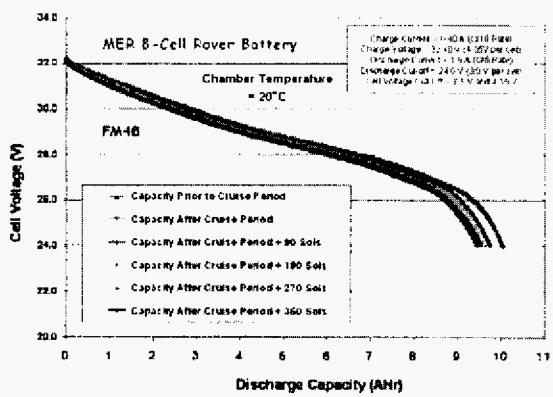
Opportunity. Prior to performing the capacity and impedance determination, the cells within the batteries were balanced (to < 25 mV dispersion) so as to obtain full capacity and optimal performance, as well as to closely mirror the conditions experienced on the two rovers. In summary, excellent performance has been obtained thus far, which is encouraging to the project and factors into the decisions to extend the mission further. As shown in Table 1, one of the batteries still exhibits 93.3 % of the initial capacity after completing the cruise period and 360 sols of surface operation simulation. The other battery shows very complementary data with 92.8 % of the original capacity being

Table 1. Entry-Descent-and-Landing testing of a MER design 10 Ahr lithium ion cell.

FM4B	Performance Prior to Cruise		Performance After Cruise and Completing 90 Sols				Performance After Cruise and Completing 180 Sols				Performance After Cruise and Completing 270 Sols				[redacted]			
Temperature (°C)	Discharge Capacity (Ah)	Discharge Energy (Wh)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)
20°C	10.048	289.6	9.742	96.96	280.1	96.69	9.611	95.65	275.8	95.24	9.543	94.98	273.4	94.38	9.448	94.03	270.3	93.32
0°C*			8.991		254.8		8.897		251.6		8.799		248.3		8.632		242.8	
-20°C*	7.864	215.9	7.295	92.77	198.6	91.98	7.063	89.81	191.7	88.76	6.929	88.11	187.9	87.04	6.710	7.30	181.1	83.89
-30°C*							5.759		150.2		5.420		140.4		5.364		139.3	

displayed, emphasizing the good reproducibility of the data between the two batteries. As shown in Fig. 10, the voltage profile during the 100% DOD capacity checks performed every 90 sols displays little change. As expected, the capacity losses are more significant at the lower temperatures, due to the increased polarization effects compounded by increased impedance growth as a function of life. However, both the batteries display operational capability at temperatures as low as -30°C late in life, with over 56 % of the room temperature capacity being delivered with a room temperature charge. In addition to assessing the low temperature capabilities with ambient temperature charging, cycling was performed with the charging occurring at the respective temperatures. Expectedly, the capacity delivered is lower under these conditions; however, good performance was obtained using low temperature charge. For example, only 6% less capacity was delivered at -20°C following charge at that temperature, while 12% less capacity was delivered at -30°C. Fortunately, since the charge period of the rovers is during daylight hours, the latter stages of the charging are occurring while the temperatures are warmer.

Figure 10. Discharge capacity (100 % DOD) at 20°C as a function of surface operation life.



In addition to assessing the capacity losses as a function of life, the impedance of the batteries and the cells has been determined by performing current-interrupt testing. As mentioned previously, it is important to consistently impose identical pulsing conditions to make meaningful conclusions. Due to the fact that it is difficult to determine the precise SOC and state of health of the batteries on Mars, an enhanced understanding of the impact that capacity loss and impedance growth have upon the polarization behavior is of great benefit. For this reason, we have been systematically performing impedance measurements at various states-of-charge and temperatures throughout the life of the batteries. As shown in Table 2, the impedance of the battery steadily increases as a function of cycle life, being more dramatic at lower temperatures. As illustrated, after completing 360 sols of the surface operation profile and the ~ 7 month cruise period, one of the batteries displayed approximately a 55% increase in the impedance measured (the second battery displaying ~ 57% increase) (at ~ 100% SOC). Although an incomplete data set was performed immediately after the cruise period, it appears as though the greatest increase in impedance was sustained in the first 90 sols of operation.

Table 2. Impedance measurements as a function of cycle life.

FM4B	Performance Prior to Cruise	Performance After Cruise		Performance After Cruise and Completing 90 Sols		Performance After Cruise and Completing 180 Sols		Performance After Cruise and Completing 270 Sols		[redacted]	
Temp (°C)	Battery Impedance (mOhms)	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance	Battery Impedance (mOhms)	Percent Increase in Impedance
20°C	118.16			155.10	31.26	164.6	39.30	172.8	46.24	183.0	54.87
0°C*	241.70	283.04	17.10	354.84	46.81	379.7	57.08	396.6	64.09	421.6	74.44
- 20°C	589.91			871.26	47.69	922.8	56.42	925.9	56.96	938.2	59.04
- 30°C						1372.4		1408.2		1406.0	

As mentioned previously, a major objective of performing the 100% DOD and impedance characterization tests was as a means of assessing the battery health to aid in life predictions in support of the mission. Given the difficulty of assessing the life characteristics from telemetry data, the data generated from the ground testing of an identical battery subjected to comparable conditions proved to be crucial in assessing the viability of the technology to support a prolonged mission (i.e., at least three years in duration) and provide input for proper battery management. As shown in Fig. 11, to-date only 6-7 % capacity loss has been observed on both batteries as a result of being subjected to 360 sols, the 7 month cruise period, and intermittent characterization (total test time > 2.6 years). Also significant is the fact that only ~ 1% capacity loss has been sustained as a result of the last 90 sols of testing, even though the temperature regime has been warmer during this period. This data suggests that the fade rate and degradation processes are more dramatic early in life and that the losses are leveling off. A simple extrapolation of the life data suggests that over 80% of the initial capacity delivered at 20°C will remain after completing 1400 sols (over 3.5 years), as illustrated in Fig. 12. Of course, the losses in low temperature capability are certain to be more dramatic, however, with careful management the batteries should be capable of supporting the mission well into the future.

Figure 11. Percent of initial capcity observed with both FMSA and FM4B of the mission simulation battery.

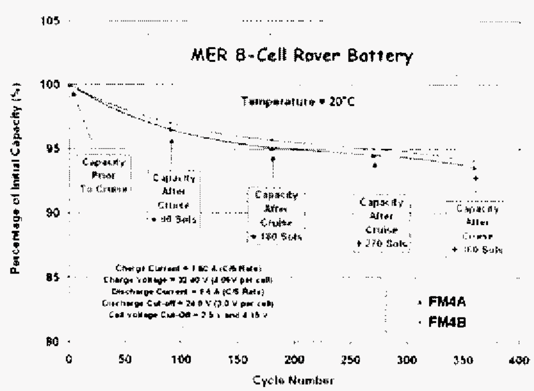
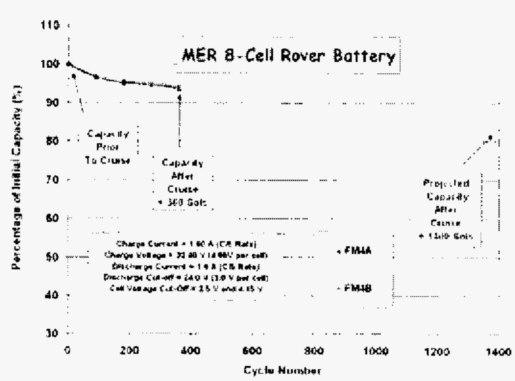


Figure 12. Individual cell impedance values obtained from a MER Rover 8-cell lithium-ion battery as a function of life



III. Conclusion

To support the operation of Spirit and Opportunity on Mars, on-going mission simulation ground testing has been performed at JPL. This testing has included, (a) performing initial characterization tests (discharge capacity at different temperatures), (b) performing ATLO simulation, (c) simulating the launch conditions, (d) simulating the cruise phase conditions (including trajectory corrections), (e) simulating the entry, decent, and landing pulse load profile (if required to support the pyros), (f) simulating the Mars surface operation mission simulation conditions, as well as, (g) assessing the performance capacity loss and impedance characteristics as a function of temperature and life. These tests have demonstrated that the technology meets or exceeds all mission requirements, most notably displaying excellent cycle life characteristics, far exceeding the requirement of 90 sols of operation. To-date, the mission simulation batteries have only displayed only 6-7 % permanent capacity loss after being subjected to 7 months of storage, 360 surface operation sols, and intermittent characterization testing (over 2.6 years of total test time). Based on data generated from the ground testing of this engineering battery, current projections indicate that the batteries on Spirit and Opportunity can support an extended mission well into the future (> 1000 sols), while still exhibiting over 80% of the initial capacity at ambient temperatures. Due to seasonal changes in temperature and solar intensity, the coming winter months are more demanding on battery and solar array performance, however, with proper management the rovers have the potential to work well into the future.

Acknowledgments

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